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Little evidence that Amazonian rainforests are approaching a tipping point

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ARISING FROM **C. A. Boulton et al.** ***Nature Climate Change*** **https://doi.org/10.1038/s41558-022-01287-8 (2022)**

By analysing microwave data, Boulton et al.[1] reported a pronounced loss of forest resilience over Amazonia since 2003, interpreted as a risk of crossing a tipping point leading to forest dieback. While Boulton et al. explored an important question using a highly innovative approach, their result should be interpreted with caution, because the vegetation optical depth (VOD) they used in their analysis is likely to suffer from soil moisture contamination and sensor discontinuity over Amazonia.

Below, we highlight potential data issues in Boulton et al.[1]. Using an independent radar dataset, we show that the decreasing trend in forest resilience is at best limited, and has been partly reversed in recent years, thus challenging the conclusion that Amazonian rainforests are approaching a tipping point.

Soil moisture contamination

VOD is a model-based variable related to the water content of vegetation (over Amazonia, mostly forest). Boulton et al. used VOD data from the VOD Climate Archive (VODCA[2]), which are extracted from passive microwave signals that originally contain a mixed signal from vegetation canopy and soil. To derive VOD, the fraction of signal originating from soil should be filtered. Otherwise, this metric is expected to be sensitive to soil moisture dynamics in addition to vegetation change[3].

The K-band (18.7 GHz) VOD used by Boulton et al. increased markedly in 2009 and 2012 (Fig. 1b; also shown in Fig. 1 of Boulton et al.). Such increases in VOD cannot be related to changes in vegetation because plant physiology constrains the water content of stems and leaves[4]. We hypothesize that the sudden increases could be caused by soil moisture contamination during the severe Amazon floods in 2009 and 2012[5–7] (Fig. 1a). As a comparison, we checked the Quick Scatterometer (QSCAT; Ku-band radio frequency, 13.4 GHz, 1999–2009) and Advanced Scatterometer (ASCAT; C-band frequency, 5.3 GHz, 2007 onwards) radar signals (Supplementary Methods). Unlike passive instruments, radar actively emits a microwave from above the canopy and measures the intensity of the backscattered waves. QSCAT and ASCAT signals are unable to penetrate the dense canopy of Amazonian forests, thus show little sensitivity to soil moisture and flood events[8,9]. As expected, we found no abrupt increase in either QSCAT or ASCAT signals in 2009 and 2012, contrasting with the K-band VOD (Fig. 1b). This shows that K-band VOD is sensitive to below-canopy soil surface conditions, and changes cannot simply be ascribed to changes in vegetation resilience.

Sensor discontinuity

The K-band VOD used by Boulton et al. was created by merging VOD products from several satellite sensors including the Special Sensor Microwave/Imager (July 1987–April 2009), the Tropical Rainfall Measuring Mission's Microwave Imager (December 1997–April 2015), WindSat (February 2003–July 2012), the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E; June 2002–October 2011) and the Advanced Microwave Scanning Radiometer 2 (AMSR2; July 2012–January 2019) (ref. 2). The influences of sensor discontinuity on the results of Boulton et al. can be summarized as follows.

1. The years 2009 and 2012, when the VODCA K-band VOD increased suddenly (Fig. 1), correspond to shifts in satellite sensor (green lines in Fig. 1b). After 2012, the K-band VOD mainly originated from one sensor, AMSR2, in contrast to four sensors before 2012 (ref. 2). These sensor shifts in combination with soil moisture contamination may influence the sudden increases in 2013 and 2014: note that there were also floods in 2013 and 2014 (ref. 7) (Fig. 1a).
2. The main finding of Boulton et al. is the continuous loss of forest resilience since 2003 indicated by the continuous increase in the lag-1 autocorrelation coefficient (AR(1); Fig. 2c of Boulton et al.; see also Fig. 2a). However, 2003 corresponds to the launch time

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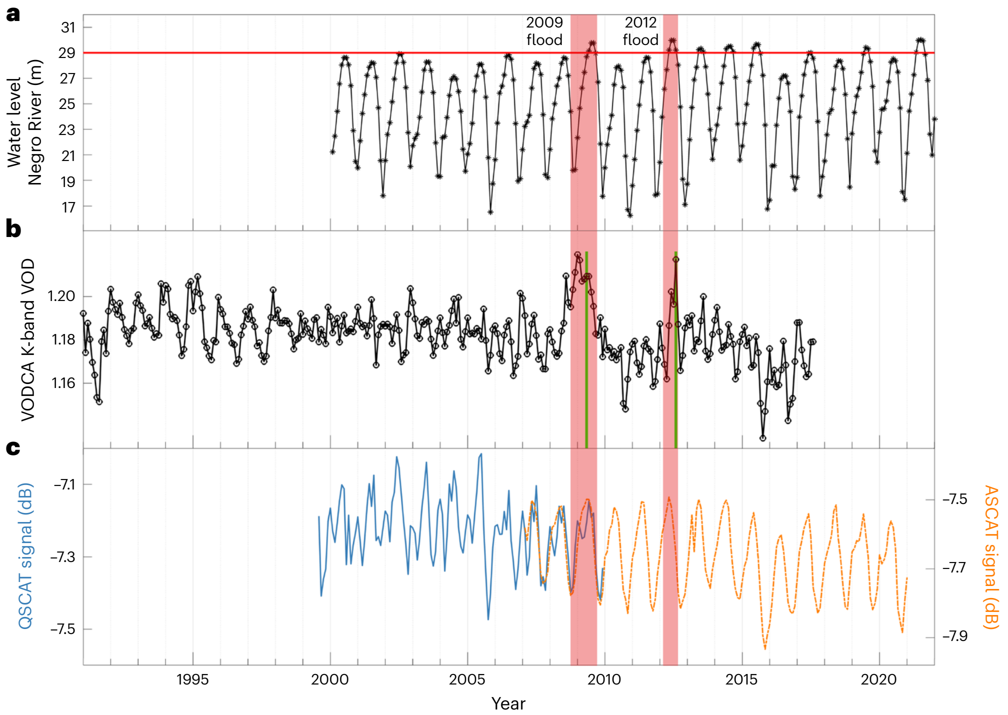

Fig. 1 | Time series of water levels, K-band VOD and radar signals. a, Water levels of the Negro River. **b**, K-band VOD used by Boulton et al.[1]. **c**, Radar signals from QSCAT and ASCAT sensors. All three time series have a monthly time step. A threshold of 29 m in water level was used in **a** to identify the peak flood periods, as in the work of Espinoza et al.[7]. The signals shown in **b** and **c** have been averaged across Amazonian pixels[1]. The red bars highlight the 2009 and 2012 Amazon flood events. The green lines in **b** mark two months when sensor shift occurred within the K-band VOD product.

of two new K-band microwave sensors (AMSR-E was launched in June 2002 and WindSat launched in January 2003, doubling the number of sensors from two to four). This has influenced the quality of the K-band VOD: there are clear discontinuities in the Hovmöller diagrams showing anomalies of the monthly means per latitude of K-band VOD (Fig. 6 of Moesinger et al.[2]). Using QSCAT radar data with a frequency similar to that of the K-band VOD used by Boulton et al. (Fig. 2a), we found no continuous increase in AR(1) after 2003, even with different lengths of sliding window to calculate AR(1).

3. In addition to the continuous loss of forest resilience since 2003, Boulton et al. showed another decrease in resilience starting from around 2012 using another dataset, the C-band VOD from the same VODCA archive (Fig. S22 of Boulton et al.; see also Fig. 2b). C-band VOD was merged across several sensors, mainly AMSR-E and AMSR2; the former was disconnected from the latter in 2012—the year in which AR(1) increased sharply in the analysis by Boulton et al. (Fig. 2b). This suggests that the increase in 2012 may be linked to sensor shift.

Are Amazonian rainforests approaching a tipping point?

On the basis of our reanalysis, the question of whether Amazonian rainforests are approaching a tipping point remains open. To shed light on this debate, we use a long-term radar dataset (1992–2018) created for global tropical rainforests (Tao et al.[10]), merging C-band (European Remote Sensing satellite, 1992–2001, and ASCAT, 2007–2018) and Ku-band (QSCAT, 1999–2009) radar signals (Supplementary Methods). The specifications of the long-term radar dataset and VODCA are comparable: they both have a resolution of ~25 km, and they both are microwave signals; the main difference is that radar signals are acquired by active sensors and VOD by passive sensors. During the creation process of the merged radar dataset, special attention was paid to its internal and temporal coherence[10]. The merged radar dataset has also been demonstrated to be robust to rainfall, flood and soil moisture change, and it was validated against ground data to be sensitive to biomass change[10]. We therefore used this merged radar dataset to re-address the question of the resilience of Amazonian rainforests. We used the same method for calculating AR(1) as Boulton et al. and the same mask for locating Amazonian rainforests.

We found a largely different temporal trajectory of AR(1) compared with Boulton et al. First, AR(1) did not increase continuously after 2003 (Fig. 2c). Second, there was a clear increase in AR(1) around 2011 (Fig. 2c), but no sudden increase in 2012 (Fig. 2d). Third, the overall rising trend of AR(1), as indicated by Kendall's τ (unitless, ranging from −1 (strong decrease) to 1 (strong increase)), was much weaker than reported by Boulton et al. (0.17 versus 0.59, Fig. 2c). Fourth, AR(1) values have decreased since around 2016 (Fig. 2c), suggesting a post-drought recovery enhancing forest resilience. This post-drought recovery was also observed in satellite net primary productivity and gross primary productivity estimates[11,12], possibly due to forest regrowth in favourable climate conditions in recent years[12].

Thus, our reanalysis does confirm the finding by Boulton et al. of an increasing trend of AR(1), interpreted as a loss of resilience for this forest. However, the much weaker trend and the recent recovery in resilience do not support the conclusion that Amazonian rainforests are approaching a tipping point. Note that none of the turning points revealed by the radar data coincide with sensor shifts. The radar-based results also suggest that increases in AR(1) are closely related to severe droughts (such as the 1997–1998, 2005, 2010 and 2015 Amazon droughts), pointing to repeated droughts as a major cause of the decreased resilience of Amazonian rainforests. We noticed that this drought-induced loss of resilience was also reported in Fig. 6 of Boulton et al., but was less obvious, and was achieved by shifting the AR(1) time series to match the occurrence of drought: AR(1) was plotted at the midpoint of the five-year time slicing window

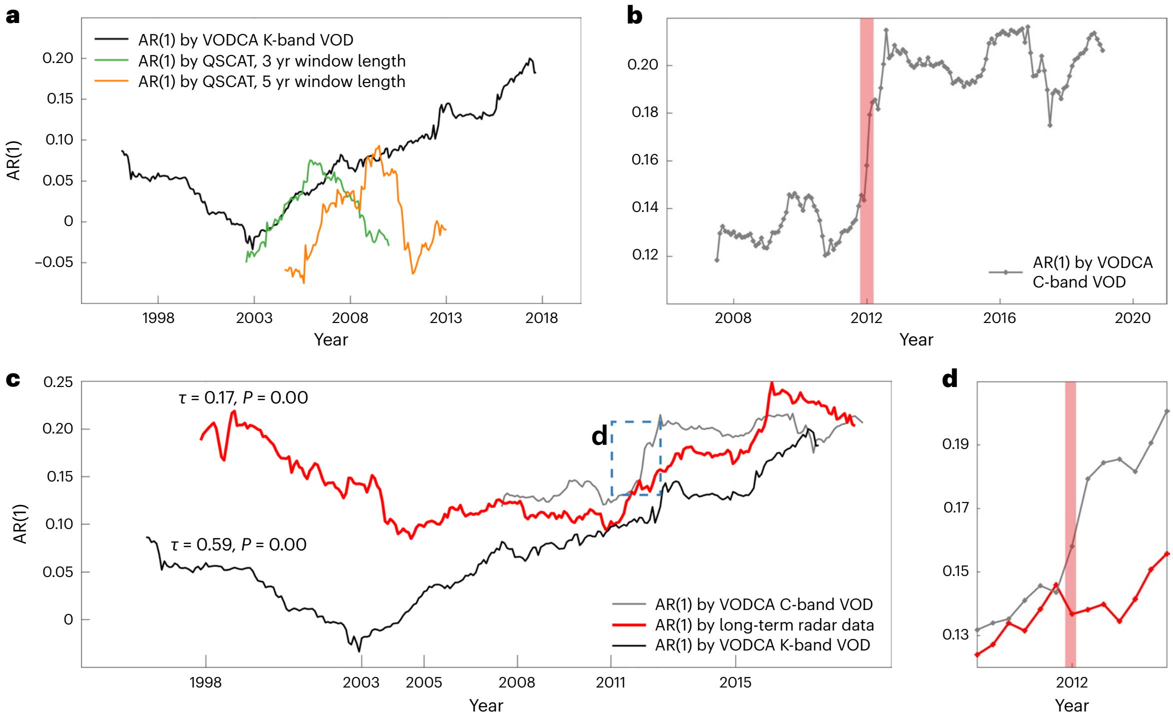

Fig. 2 | Temporal changes in AR(1) calculated from different microwave datasets. a, The AR(1) calculated from VODCA K-band VOD (the same as Fig. 2c of Boulton et al.[1]), compared with those calculated from Ku-band QSCAT radar signals. An increasing trend in AR(1) can be interpreted as a loss of forest resilience. Different lengths of sliding window were used for calculating AR(1) from QSCAT signals, but no continuous increase in AR(1) was found after 2003. **b**, The AR(1) calculated from VODCA C-band VOD (the same as Fig. S22 of Boulton et al.[1]). An sudden leap in AR(1) occurred in 2012 (highlighted by the red bar). **c**, AR(1) calculated from radar data[10]. As a comparison, those calculated from VODCA K-band and C-band VOD are shown again here. **d**, A zoomed-in portion of **c**, with the *x* axis centred around the year of 2012. In all four subsets, AR(1) was calculated with a 5 yr sliding window unless explicitly noted. All AR(1) values were plotted consistently at the end of each sliding window.

in Fig. 6 of Boulton et al., but it was plotted at the end of the window in all other figures.

In summary, Boulton et al. tested the important question of the resilience of Amazonia using long-term passive microwave data. The dataset they used, namely VODCA, is a long-term, multifrequency VOD dataset available at a global scale, and has proved useful for a range of applications, including global biomass estimation[2]. However, over the Amazon, these data seem to have issues of soil moisture contamination and sensor discontinuity, and thus make trend analysis at best uncertain. We believe that these issues have impacted the conclusions of Boulton et al. Amazonian rainforests play an essential role in the global carbon cycle, but remote sensing studies remain challenging in this region[13]. It cannot be overstated that remote sensing methods should be carefully validated against ground data, especially if the objective is to evaluate the likelihood of a tipping point[14]. Here we provide a different analysis using radar observations, validated against ground data for the key drought years of 2005 and 2010 (ref. 10). Our results differ from that of Boulton et al. in important aspects: the decreasing trend in resilience was weak, mainly driven by drought events, and has been partly reversed in recent years. Whether the Amazonian rainforest is approaching a tipping point is therefore not clear, but according to the radar analysis the answer depends on the frequency and intensity of future droughts[10]. With this comment, we wish to provide a different perspective for the future of this important region, and we hope our results will also be scrutinized in detail.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01853-8.

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Data availability

The long-term radar dataset has been made publicly available at https://doi.org/10.6084/m9.figshare.14061428.v6. Water levels of the Negro River were downloaded from https://www.portodemanaus.com.br/?pagina=nivel-do-rio-negro-hoje. Data for reproducing the results of Tao et al.[10] can be downloaded from https://doi.org/10.6084/m9.figshare.14061428.v6 and https://github.com/TonySl/Radar_Rainforest.

Code availability

Code for this work uses functions maintained at https://github.com/TonySl/Radar_Rainforest and https://doi.org/10.5281/zenodo.5837469.

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Author contributions

S.T., J.-P.W., J.C. and P.C. designed the research. S.T., J.-P.W., J.C., P.C., Z.T., Z.W., J.Z., Q.G. and Y.Y.L. analysed the data. S.T., J.-P.W., J.C. and P.C. wrote the initial draft. All authors discussed and made substantial contributions to successive drafts.

Competing interests

The authors declare no competing interests.

Additional information

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